Detection of High-Frequency Phonons from the Inhomogeneous Gap States of a Nonequilibrium Superconductor

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Measurements are reported, for the first time, for detection of nonequilibrium phonons emitted from the inhomogeneous gap states of a nonequilibrium superconductor by means of a phonon transmission technique. The observed phonon signal exhibits a clear spatial structure with a certain periodicity. The connection between the I-V characteristic and the phonon signal is discussed.

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It is now a well-established experimental fact that a homogeneous superconductor driven far from equilibrium under intense tunnel injection undergoes a transition to inhomogeneous gap states. Two- or multiple-gap states to date have been observed for aluminum,[1-4] lead-indium,[5] and tin films.[6,7] To study the possible spatial distribution of quasiparticles, Akoh and Kajimura[8] have recently fabricated a long narrow injector junction with seven microdetector junctions attached on it. Their results were, however, not conclusive because the detector junctions were not small enough to define a single gap region. In this Letter, we present measurements of the spatial distribution of nonequilibrium phonons emitted from a superconducting tin film with two different gaps utilizing a small tunnel-junction sensor placed separated from it by a superfluid layer of several tens of micrometers.

To begin with, we find the relation between the number density of emitted phonons and the quasiparticle concentration in a nonequilibrium superconducting film using the Rothwarf-Taylor equations[3,9] modified to include quasiparticle diffusion. It is directly derived from the steady-state solutions by eliminating the quasiparticle-flow term. The result is given by

$$\frac{N_{\mathrm{ph}} - N_{\mathrm{ph}}{}^{T}}{\tau_{\mathrm{es}}} = \frac{R}{1+\tau_{\mathrm{es}}/\tau_{B}}\left[N^2 - N_T{}^2 + \frac{I_{\mathrm{ph}}}{R}\right], \qquad (1)$$

where N and N_T are the nonequilibrium and thermal-equilibrium quasiparticle concentration, N_{ph} and $N_{\mathrm{ph}}{}^{T}$ are the nonequilibrium and thermal-equilibrium phonon number densities, respectively, R is the quasiparticle recombination coefficient, τ_B is the phonon pair-breaking time, τ_{es} is the phonon escape time, and I_{ph} is the phonon injection rate. Equation (1) indicates that the emitted-phonon number density per unit time is directly connected with the quasiparticle concentration in the film. In our experiments, because of high injector bias voltages, I_{ph} has a finite value due to relaxation phonons created by decay of high-energy quasiparticles. The phonons emitted toward the liquid-helium side pass through the Kapitza boundary, then propagate in superfluid helium and reach the surface of a sensor film where they again experience the Kapitza resistance. If the energy of those transmitted phonons is greater than the gap of the sensor film, they are capable of pair breaking, resulting in a gap reduction in the film. For our experimental temperature ($T = 1.6$ K), however, no detailed reports on propagation of high-frequency phonons emitted from a dc-biased superconducting tunnel junction are available.[10]

For generation of phonons, we used a Sn-I-Sn-I-Sn double tunnel junction composed of an injector and a detector with the middle film in common. The phonon sensor was a 20×20 μm^2 S-I-N type junction (either Sn-I-NiCr-Cu or In-I-NiCr-Cu) of resistance 0.2–5 Ω. A thin NiCr film provided an oxide barrier of high quality. These junctions were mounted on sample stages which were movable in liquid helium by a specially designed cam and gear system. A double tunnel junction was placed on one sample stage which was movable in the x-y plane, whereas a phonon sensor was placed on the other sample stage which was movable along the z axis only as shown in Fig. 1(a). These two samples were set several tens of micrometers apart. The mechanical system was very precise and reliable. The overall spatial resolution was limited by the size of the sensor (i.e., 20 μm). A typical derivative characteristic of the sensor junction is shown in Fig. 1(b). The change in dV/dI at zero bias voltage becomes proportional to the incident phonon injection rate.

The experiments were performed in the follow-

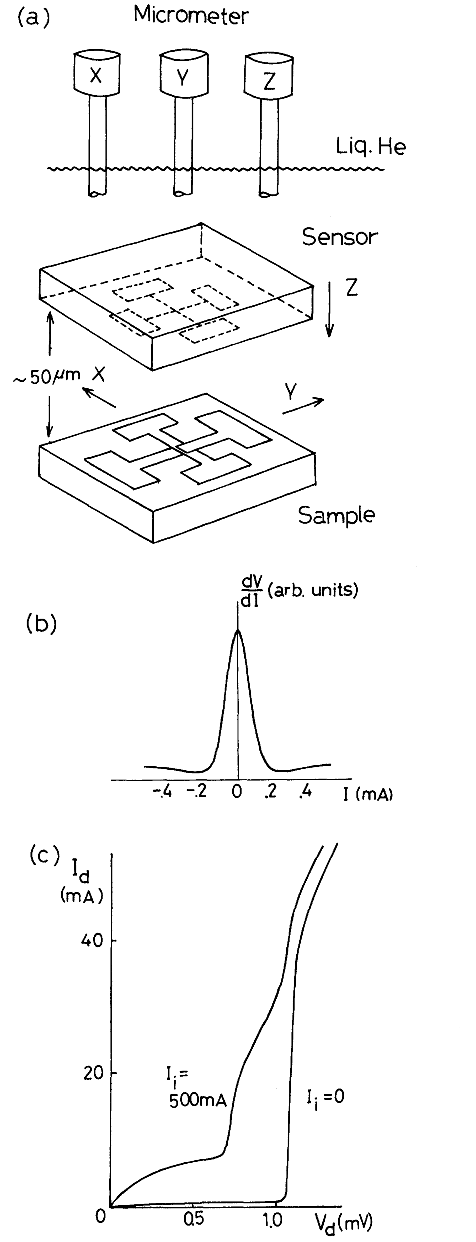

FIG. 1. (a) Schematic drawing of the experimental setup for phonon generation and detection. The figure is not to scale. (b) Typical derivative characteristic of a sensor junction. (c) Typical detector I-V characteristics of a double-tunnel junction with and without injection current.

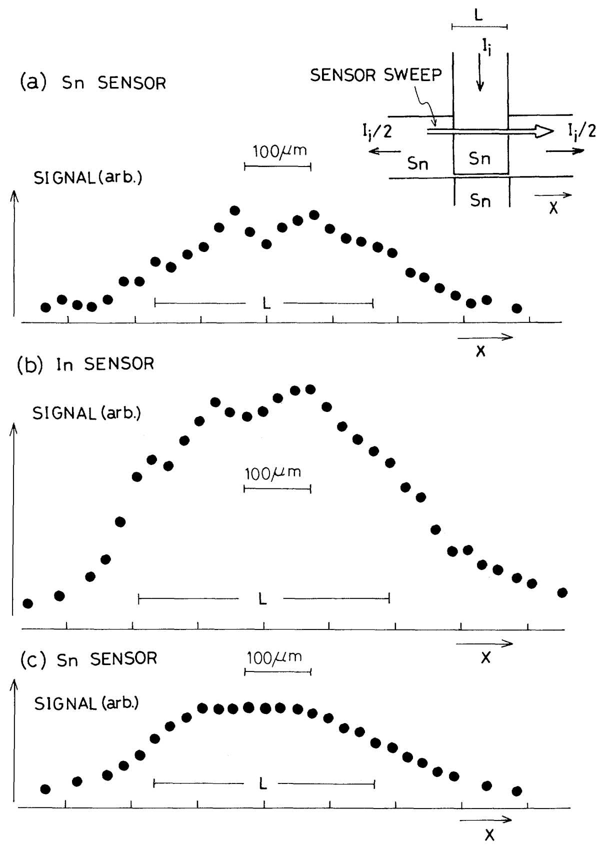

FIG. 2. Detected phonon signal as a function of position. (a) Sn sensor; (b) In sensor; (c) Sn sensor.

ing steps. First, by means of the double-tunnel junction, the detector I-V trace was recorded at a given injection current to confirm the existence of two-gap structure [see Fig. 1(c)]. Next, with the phonon sensor fixed at a certain position, its differential resistance dV/dI at zero bias voltage was recorded with and without the injection current with a lock-in amplifier. Figure 2(a) shows the results of the net response $[(dV/dI)_{I_i=0} - (dV/dI)_{I_i\neq 0}]$ when $I_i = 500$ mA ($eV_i \simeq 13\Delta$) as a function of the sensor position along the x axis. The sensor was a Sn-I-NiCr-Cu junction and the injection current was fed symmetrically to both sides of the middle film. The larger (Δ_α) and the smaller (Δ_β) gaps were $\Delta_\alpha/\Delta_T \simeq 0.95$ and $\Delta_\beta/\Delta_T \simeq 0.7$, respectively, where Δ_T is the unperturbed gap parameter. The observed maximum response corresponds to about a 1% decrease in $(dV/dI)_{I_i=0}$, being equivalent to a gap decrease of about 1 μV. The sensor signal rapidly decreased as the separation between the injector and the sensor went beyond 100 μm. The detected phonons exhibit a clear periodic structure with the period about 100 μm. This value should be, however, reduced by about 20% due to the phonon spreading effect during propagation in liquid helium which was confirmed by another experiment. The decay tails extending over both ends of the injected area suggest the quasiparticle flow toward the unperturbed film. When the injection current was fed to only one side of the middle film, the periodic pattern was still present but the relative peak height was changed. Figure 2(b) shows the case when a In-I-NiCr-Cu junction was used as a phonon sensor. We still find a similar structure to that found for tin. The observed structure was qualitatively the same for different injection currents so long as the two-gap state was formed. We have also studied the in-line type injector junction of length about 500 μm, which again resulted in the periodic structure of the same order of periodicity along the direction of current flow. In this case five successive peaks appeared with the peaking shape around the center in contrast to the above case.

There are, at least, two possibilities about the nature of detected phonons in this strongly perturbed system confined to a small space, i.e., ballistic 2Δ phonons and second-sound heat pulses as suggested in Ref. 10. In any case, they would image the superconducting inhomogeneous state. We also note that the detector I-V traces were not affected by the presence of a sensor substrate in close vicinity. In the 2Δ-phonon case, based on the theoretical phonon distributions at high bias voltages,[11] the sensor film will be affected by those phonons from both α and β regions in spite of the fact that $\Delta_{\rm Sn} = \Delta_T > \Delta_\alpha > \Delta_{\rm In} > \Delta_\beta$. The phonons from the smaller gap region will yield larger signals. Figure 2(c) shows an example for which injection did not cause a distinct gap structure but the gap was reduced about 20%. The response was found to be almost flat in this case, suggesting the absence of an instability. We have also detected the phonons from a superconducting film driven normal by large transport current exceeding the critical current of the film, which again resulted in a flat response. These facts indicate that the emitted phonons from the inhomogeneous gap state are highly nonthermal and their spatial distribution reflects the quasiparticle distribution in space.

In Fig. 3, we present the result of a two-dimensional survey of the sensor signal, together with a sketch of contour mapping deduced from the experimental data. The signal along the x axis is approximately symmetrical, whereas that along the y axis is rather asymmetrical probably because of the asymmetrical boundary condition along the y axis although it still exhibits a periodic structure. We now try to compare the observed structure with the detector I-V trace given in Fig. 1(c).[12] Figure 1(c) suggests that both the α and β regions occupy about $\frac{1}{4}$ of the total injected area and the remainder region corresponds to a transition region. In Fig. 3, the β region will correspond to the ridge surrounding an unclosed caldera, while the α region will correspond to the caldera and some outer circumference region. The rather shallow caldera is probably due to the phonon spreading effect in liquid helium.

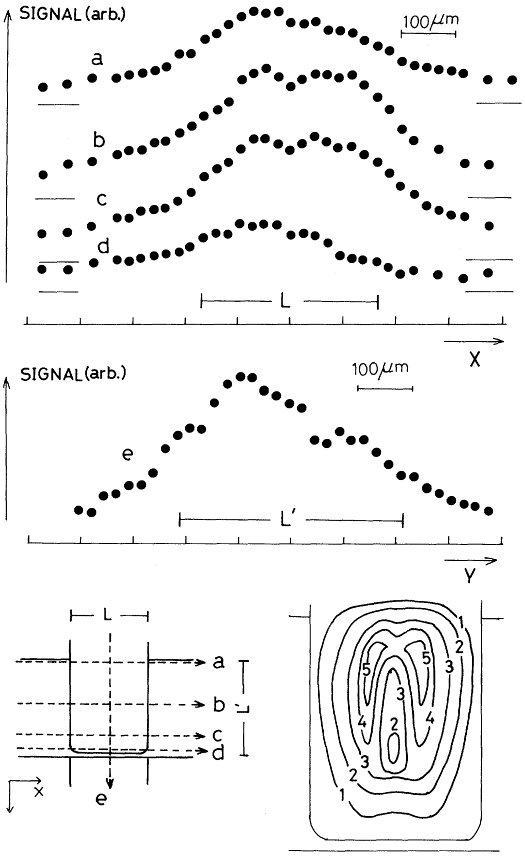

FIG. 3. Detected phonon signals for various sweep paths of a Sn sensor as indicated bottom left. Bottom right: A sketch of contour mapping of phonon signal. The number in each contour indicates the relative magnitude of phonon signal. The larger number corresponds to larger signal.

One possible interpretation is to assume an abnormal diffusion of quasiparticles from high-gap to low-gap region as far as only a one-dimensional problem is involved. Very recently Konno[13] calculated the spatial modes based on the μ^* instability model[14] in a finite system using Green's function technique and obtained a periodic structure of the same order. The other possibility relies on the assumption of normal diffusion but allowing two-dimensional flow of quasiparticles.

In conclusion, we have demonstrated that the phonons emitted from the inhomogeneous gap state are highly nonthermal and the measurements of these phonons by the two-dimensional sweep of a microsensor provide a study of nonequilibrium gap structure in detail. It will be a next interesting subject to investigate the nature of these phonons and their transmission mechanism.

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[1] R. C. Dynes, V. Narayanamurti, and J. P. Garno, Phys. Rev. Lett. 39, 229 (1977).

[2] K. E. Gray and H. W. Willemsen, J. Low Temp. Phys. 31, 911 (1978).

[3] I. Iguchi and D. N. Langenberg, Phys. Rev. Lett. 44, 486 (1980).

[4] I. Iguchi *et al.*, Phys. Rev. B 23, 3240 (1981).

[5] H. Akoh and K. Kajimura, Solid State Commun. 38, 1147 (1981).

[6] I. Iguchi *et al.*, Phys. Rev. B 24, 1193 (1981).

[7] S. Kotani, Y. Yamaki, and I. Iguchi, Physica (Utrecht) 107B+C, 535 (1981).

[8] H. Akoh and K. Kajimura, Physica (Utrecht) 107B+C, 537 (1981), and to be published.

[9] A. Rothwarf and B. N. Taylor, Phys. Rev. Lett. 19, 27 (1967).

[10] In the heat pulse experiments, for temperatures below 0.6 K, the phonons of wavelength less than 12 Å have a sufficiently long lifetime to propagate macroscopic distances [R. C. Dynes and V. Narayanamurti, Phys. Rev. Lett. 33, 1195 (1974)]. As shown later, our experiments indicate spatially inhomogeneous distributions at $T = 1.6$ K apparently contradicting the above statement if a ballistic flow of 2Δ phonons is considered. Under strongly perturbed nonequilibrium condition involving intense 2Δ phonon (or excitation) transmission in liquid helium confined to a limited small space, however, the situation will be quite different from the thermal or the near-thermal one, and hence our results do not contradict the above result. Moreover, it is also possible to conjecture the transmission of second-sound heat pulses of lower frequency under this condition.

[11] J.-J. Chang and D. J. Scalapino, J. Low Temp. Phys. 31, 1 (1978).

[12] Although the observed signal is related to the quasiparticle concentration but not gap value, we here take a rough approximation that larger signal corresponds to lower gap.

[13] H. Konno, unpublished.

[14] D. J. Scalapino and B. A. Huberman, Phys. Rev. Lett. 39, 1365 (1977).

Resonant Fluorescence Line Narrowing in $\mathrm{La}_{1-x}\mathrm{P}_5\mathrm{O}_{14}:\mathrm{Nd}_x{}^{3+}$

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Donor-donor and donor-acceptor dynamics in $\mathrm{La}_{1-x}\mathrm{P}_5\mathrm{O}_{14}:\mathrm{Nd}_x{}^{3+}$ are measured directly with a high-resolution, near-ir laser system. Time-resolved fluorescence line-narrowing measurements show an absence of rapid donor-donor transfer below 20 K and an onset of spectral diffusion at ≈ 20 K for an $x = 0.75$ sample. The linear concentration quenching and exponential decay in the absence of fast diffusion are explained with existing energy-transfer theories and are consistent with room-temperature studies.

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$\mathrm{La}_{1-x}\mathrm{P}_5\mathrm{O}_{14}:\mathrm{Nd}_x{}^{3+}$ (LNPP) is one compound of a class of high-gain Nd laser materials,[1] which show a small decrease in their fluorescence quantum efficiency (QE) as the Nd^{3+} concentration is increased up to the stoichiometric limit. Directly related to this technologically important aspect are several interesting anomalous luminescence properties. The weak concentration quenching of the QE in LNPP is linearly dependent[1-4] on the fractional Nd^{3+} concentration x, in contrast to many other similar systems,[5] e.g., $\mathrm{YAlG}:\mathrm{Nd}^{3+}$ (neodymium-doped yttrium aluminum garnet),